Cutoff in the TeV Energy Spectrum of Markarian 421 During Strong Flares in 2001

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ABSTRACT

Exceptionally strong and long lasting flaring activity of the blazar Markarian 421 (Mrk 421) occurred between January and March 2001. Based on the excellent signal-to-noise ratio of the data we derive the energy spectrum between 260 GeV - 17 TeV with unprecedented statistical precision. The spectrum is not well described by a simple power law even with a curvature term. Instead the data can be described by a power law with exponential cutoff: $\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.14\,\pm\,0.03_{\mathrm{stat}}} \times \mathrm{e}^{-\mathrm{E}/\mathrm{E}_0}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$ with $\mathrm{E}_0 = 4.3 \pm 0.3_{\mathrm{stat}}\mathrm{TeV}$. Mrk 421 is the second γ-ray blazar that unambiguously exhibits an absorption-like feature in its spectral energy distribution at 3-6 TeV suggesting that this may be a universal phenomenon, possibly due to the extragalactic infra-red background radiation.

Subject headings: BL Lacertae objects: individual (Mrk 421) — γ rays: energy spectrum, IR background radiation

1. Introduction

Since the discovery of TeV γ-rays from the BL Lac objects, Mrk 421 (Punch et al. 1992) and Mrk 501 (Quinn et al. 1996), detailed very high energy observations of these nearby blazars (z = 0.031, z = 0.034) have been made. Measurements of flux variation with time, particularly simultaneous measurements at several wavelengths, constrain models of particle acceleration and γ-ray production in the jets. Spectral energy density measurements constrain both the models of the jets and of the infra-red (IR) photon density in the intervening intergalactic medium. The possibility of absorption of γ-rays by IR radiation has been predicted for some time (see, e.g., Nikishov 1962; Gould & Schrèder 1967; Stecker, De Jager & Salamon 1992; Biller et al. 1998; Vassiliev 1999).

The general picture which has emerged for the spectral energy density of emitted radiation from BL Lacs has two components, a lower one with energies extended up to about 100 keV attributed to synchrotron radiation from electrons, and a higher one with energies sometimes extending to the TeV range, usually attributed to inverse Compton scattering (see, e.g., Maraschi, Ghisellini & Celotti 1992, Marscher & Travis 1996). There are also competing models (Mannheim & Biermann 1992; Mannheim 1993; Mannheim 1998) which assume that the higher energy component arises from protons, either by proton-induced synchrotron cascades (PIC models) or by decays and/or interactions of secondary particles such as neutral pions and neutrons, or synchrotron radiation from proton beams (Mücke & Protheroe 2000; Aharonian 2000). See Catanese and Weekes (1999) and Mukherjee (2001) for reviews of TeV observations and an overview of relevant models.

Mrk 421 and Mrk 501 are particularly useful in separating the spectral characteristics intrinsic to the object from absorption effects in the intervening medium because they have almost the same redshift. They also exhibit strong flares in the TeV energy regime, well above typical quiescent levels, making detailed spectral measurements possible for both

(Gaidos et al. 1996; Catanese et al. 1997; Protheroe et al. 1997; Aharonian et al. 1997).

Measurements by various TeV astronomy groups have shown that the energy spectrum of Mrk 501 is not a simple power law (Samuelson et al. 1998; Aharonian et al. 1999a; Djannati-Ataï et al. 1999; Aharonian et al. 2001) but has significant curvature. The two-component nature of multiwavelength blazar spectra implies that, over a sufficiently wide energy range, TeV spectra must be intrinsically curved. The measured curvature however depends on the distance of the energy range of the data from the IC peak. During the strong flaring activity the synchrotron peak of Mrk 501 appears to shift to above 100 keV (Catanese et al. 1997; Pian et al. 1998), with the IC peak shifting to several hundred GeV (Samuelson et al. 1998). Measurements of the HEGRA collaboration have the highest energies extending to ≈ 20 TeV; their spectrum is fit better with an exponential cutoff at $\approx 6-8$ TeV (Aharonian et al. 1999a; Aharonian et al. 2001), rather than a simple parabolic correction to the power law as used in Samuelson et al. (1998).

Several groups have determined energy spectra for Mrk 421, both at low average flux levels (< 1 Crab) (Aharonian et al. 1999b; Krawczynski et al. 2001; Bazer-Bachi et al. 2001) and from intense flares (2.8 - 7.4 Crab) (Zweerink et al. 1997; Krennrich et al. 1999a). Analysis of the intense flare data showed that Mrk 421 had a spectral index different from Mrk 501. The data could be acceptably fit with a simple power law, although there was weak evidence for curvature (Krennrich et al. 1999a). The shape of the spectral energy distribution for Mrk 421 (Aharonian et al. 1999b; Krennrich at al 1999b) and Mrk 501 generally appears independent of the flux level (Aharonian et al. 1999a), although some evidence for spectral variability has been reported by Djannati-Ataï et al. (1999) and Krawczynski et al. (2001) for Mrk 501.

In this Letter, we present results from γ-ray observations of Mrk 421 taken during intense flares in January - March 2001 with the Whipple Observatory 10 m telescope yielding a spectrum spanning the energy range between 260 GeV and 17 TeV. The spectrum has high statistical precision and shows a distinct cutoff with a characteristic energy of about 3-6 TeV.

2. Observations & Data Analysis

The observations were made with the Whipple Observatory 10 m γ-ray telescope equipped with the GRANITE-III high resolution camera (Finley et al. 2001). The fine granularity (0.12°) of the 379 photomultiplier camera provides good sensitivity for point sources. The sensitive energy range of the instrument is $\approx$ 200 GeV to greater than 20 TeV. Based on finer sampling of γ-ray images, the linear response of the telescope at the highest energies is improved in comparison with previous camera configurations.

The use of a different type of photomultiplier (Hamamatsu R-960, previously Hamamatsu R1398), a complete re-coating of the mirrors and the installation of a new set of light concentrators necessitated a comprehensive and detailed new calibration of the telescope. Three methods were used: the first was based on laboratory measurements of the individual instrument components, the second utilized the calibrated Cherenkov light signal from single secondary cosmic-ray muons, and the third used simulated cosmic-ray showers to match observed distributions of the parameters of the background images. All three methods provide an energy calibration consistent within 20% for the absolute energy of primary γ-rays.

The calibration can be evaluated by checking the energy spectrum of the Crab Nebula, which is a standard candle for TeV γ-ray astronomy. The measurements of the spectrum of the Crab Nebula with the Whipple telescope over several years data using different camera configurations, are all statistically consistent, showing the same flux constant and energy spectral index. Therefore, we also show the Crab spectrum in this paper for comparison with the Mrk 421 spectrum. The Crab data consist of 15.4 hours of on-source observations (zenith angle $< 35^{\circ}$) with the same amount of data for the background estimate.

Mrk 421 was more active in 2000 and 2001 than in previous years of observations, with the most intense flaring episodes in 2001. The unusually high flaring states in 2001 provide remarkable statistics, and we have chosen the strongest flares for the analysis of the spectral energy distribution. Observations of flaring states on January 21, January 31, February 1-3, February 27, March 19, March 21, March 26-27, 2001 provide together $\approx 23,000$ photons above 260 GeV. To test the validity of combining various flares we have also divided the data into two subsets and found no statistical inconsistency in the derived energy spectral indices. The statistical significance of the excess events corresponds to more than 86 standard deviations.

The selected 2001 flaring data consist of 30.8 hours of on-source observations at zenith angles less than 35°. For background comparison, the same amount of off-source data is used from observations made at similar zenith angles. The on-source data provide an average rate of 12.5 γ/min, corresponding to 3.7 Crab. The excellent signal to background ratio can be seen from figure 1. This plot shows the alpha distribution (for explanation of alpha parameter see caption of figure 1 or Reynolds et al. 1993) of events with energies greater than 1 TeV from the source (solid line) after applying γ-ray selection criteria. The dotted line shows the corresponding distribution for the background measurements.

The data analysis, γ-ray selection and energy estimate use the methods developed by Mohanty et al. (1998). These γ-ray selection criteria are derived from parameter distributions of simulated γ-ray showers as a function of their total light intensity (size) in the camera. The criteria vary with size and are set so that they keep 90% of the γ-ray images whose centroids lie within $0.4^{\circ} - 1.0^{\circ}$ of the center of the camera. To avoid the difficulties of modeling the trigger electronics we apply an additional cut, requiring that a signal of at least 15.1 photo electrons (p.e.), 13.6 p.e. and 12.1 p.e. be present in the three highest image pixels, respectively.

3. Results

The differential energy flux values derived from the intense flaring states of Mrk 421 in 2001, and for comparison the Crab Nebula, are shown in figure 2. The spectrum of the Crab Nebula can be well fit by a power law of the form:

$$\frac{\mathrm{dN}}{\mathrm{dE}} = (3.11 \pm 0.3_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times\ 10^{-7}\ \mathrm{E}^{-2.74\,\pm\,0.08_{\mathrm{stat}}\,\pm\,0.05_{\mathrm{syst}}}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

giving a χ^2 of 6.9 for 10 degrees of freedom (probability 73%). This result is consistent, within its limited statistics, with previous measurements made by the Whipple collaboration (Hillas et al. 1998; Mohanty et al. 1998; Krennrich et al. 1999a), showing that the analysis methods, the calibration of the detector, and the reconstruction of energy spectra are all consistent at the 2 sigma level including systematic uncertainties. The first set of errors on the measured spectral index are statistical and the second are systematic. The systematic errors are determined by varying the gain of the system by 20%, and by varying the cut efficiencies (see Mohanty et al. 1998).

Fitting a power law to the energy distribution of Mrk 421 yields the following result:

$$\frac{\mathrm{dN}}{\mathrm{dE}} \propto\ \mathrm{E}^{-2.64\,\pm\,0.01_{\mathrm{stat}}\,\pm\,0.05_{\mathrm{syst}}}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

giving a χ^2 of 410.7 for 10 degrees of freedom. The spectrum is clearly not compatible with a simple power law form. A curvature fit for the Mrk 421 spectrum yields:

$$\frac{\mathrm{dN}}{\mathrm{dE}} \propto\ \mathrm{E}^{-2.47\,\pm\,0.02_{\mathrm{stat}}\pm\,0.05_{\mathrm{syst}}\,-(0.51\pm0.03_{\mathrm{stat}}\pm0.05_{\mathrm{syst}})\log_{10}(\mathrm{E})}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}.$$

giving a $\chi^2 = 56.5$ for 9 degrees of freedom with a chance probability of 6×10^{-9}. As shown in figure 2, the Mrk 421 spectrum exhibits clear curvature, but a parabola is not a suitable shape. Assuming that part of the curvature in the spectrum is due to a cutoff, the data can be fit by:

$$\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.14 \pm 0.03_{\mathrm{stat}}} \times \mathrm{e}^{-\mathrm{E}/\mathrm{E}_0} \ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

with $\mathrm{E}_0 = 4.3 \ \pm 0.3_{\mathrm{stat}}\,(-1.4 \ +1.7)_{\mathrm{syst}}$ TeV.

While the χ^2 (25.2 for nine degrees of freedom or a probability of 0.3%) is not particularly good, the fit using an exponential cutoff is much better than the fits using the two simple forms considered above.

We should point out here that for the first time statistical errors of the flux measurements in TeV astronomy reached the level of 2%, likely making systematic uncertainties dominant. Because of this, indicated confidence levels should be accepted with a caution as they are based only on statistics of detected photons. We have also examined the flux values at 5.6 and 8.2 TeV, which appear high to the eye, $2.6\sigma_{\mathrm{stat}}$ and $1.8\sigma_{\mathrm{stat}}$, respectively above the exponential cutoff fit. Considering the statistical uncertainties we do not regard this as a significant feature in the data. In future, a more complete analysis will be pursued to understand systematic errors at the percent level. In derivation of the cutoff energy we have included two most prominent sources of systematics: uncertainties in the reconstruction of the spectrum with a cutoff derived from simulation tests (test spectra), and uncertainty in absolute energy calibration of the instrument (20%).

We also tried a "super-exponential" form (e.g., see Stecker, De Jager & Salamon 1992; Aharonian et al. 2001), but with no improvement in quality of fit. The result is:

$$\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.24 \pm 0.09_{\mathrm{stat}}} \times \mathrm{e}^{-(\mathrm{E}/\mathrm{E}_0)^{1.3 \pm 0.4}} \ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

with $\mathrm{E}_0 = 5.8 \pm 1.5_{\mathrm{stat}}$TeV. The χ^2 of the fit is 24.0 for eight degrees of freedom (probability of 0.2%).

4. Discussion

For the first time, the Mrk 421 energy spectrum at very high energy has been determined over a sufficiently wide energy range, and with sufficient statistical precision, that an important feature (a cutoff) could be discerned. The spectrum is best described by a power law attenuated by an exponential cutoff at an energy of $\mathrm{E_0} = 4.3 \pm 0.3_{\mathrm{stat}}(-1.4+1.7)_{\mathrm{syst}}$ TeV.

The cutoff feature could have several origins, e.g., the termination of the particle energy distribution in the primary beam, absorption near the γ-ray source (Dermer & Schlickeiser 1994) or absorption in intergalactic space by IR background radiation fields. If the cutoff energy varied in time, or differed for Mrk 421 and 501, it would not be due to extragalactic absorption. We examined our previous published flare spectra of Mrk 421 (Krennrich et al. 1999a; Zweerink et al. 1997) and found them consistent with the present spectrum. Fitting the previous Mrk 421 spectrum (Krennrich et al. 1999a) with the parametrization of $\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.14\,\pm\,0.03_{\mathrm{stat}}} \times \mathrm{e}^{-\mathrm{E}/4.3\,\mathrm{TeV}}\ \mathrm{m^{-2}\,s^{-1}\,TeV^{-1}}$ results in an acceptable χ^2 of 19.4 for 13 degrees of freedom (P = 11%).

We also examined our previously published spectrum for Mrk 501 (Samuelson et al., 1998) and find that its spectrum can be fit by $\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-1.95\,\pm\,0.07_{\mathrm{stat}}} \times \mathrm{e}^{-\mathrm{E}/\mathrm{E_0}}\ \mathrm{m^{-2}\,s^{-1}\,TeV^{-1}}$ with $\mathrm{E_0} = 4.6 \pm 0.8_{\mathrm{stat}}$ TeV. However, fitting the Mrk 501 spectrum with $\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-2.14\,\pm\,0.03_{\mathrm{stat}}} \times \mathrm{e}^{-\mathrm{E}/4.3\,\mathrm{TeV}}\ \mathrm{m^{-2}\,s^{-1}\,TeV^{-1}}$ results in a poor fit with a χ^2 of 37.6 for 13 degrees of freedom ($\mathrm{P} = 3 \times 10^{-4}$). The cutoff energy for Mrk 501 is consistent with the cutoff energy for Mrk 421, but a different spectral index is required for an acceptable fit. Thus, we find no inconsistency with the assumption that the cutoff might be due to the IR background. More detailed studies of spectral variability of Mrk 421 are in progress and will be presented elsewhere.

Energy spectra for Mrk 421 reported by the HEGRA collaboration (Aharonian et al. 1999b) are based on data taken in 1997 and 1998 with the source at a lower average flux level (≈ 0.5 Crab). However, the primary sensitivity of the HEGRA array is at energies above 1 TeV requiring a comparison above that energy. Those results indicate a power law spectrum of $\frac{\mathrm{dN}}{\mathrm{dE}} \propto \mathrm{E}^{-3.09 \pm 0.07 \pm 0.1}$. When the Mrk 421 spectral data presented here are fit with a power law using only data points above 1 TeV, a spectral index of $-3.01 \pm 0.03_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}$ with a χ^2 of 106.8 for 6 degrees of freedom is measured ($-2.73 \pm 0.04_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}$ if the 1.2 TeV - 8.2 TeV range is fitted, χ^2 of 11.1 for 4 degrees of freedom) which is consistent with the HEGRA result, considering statistical and systematic uncertainties between two different instruments.

In summary, we have presented a Mrk 421 spectrum over the energy range 260 GeV to 17 TeV which shows an exponential-like cutoff in the range 3-6 TeV, similar to the cutoff found earlier for Mrk 501 (see figure 3) which has almost the same redshift. The new Mrk 421 spectrum is consistent with those reported earlier both by our group and others. The occurrence of a cutoff at similar energy in the very high energy spectra of the two equally distant γ-ray blazars Mrk 421 and Mrk 501 might indicate that TeV γ-rays are absorbed by IR background radiation fields. Future investigations regarding the implications for the energy density of extragalactic IR background radiation are underway (Vassiliev 2001).

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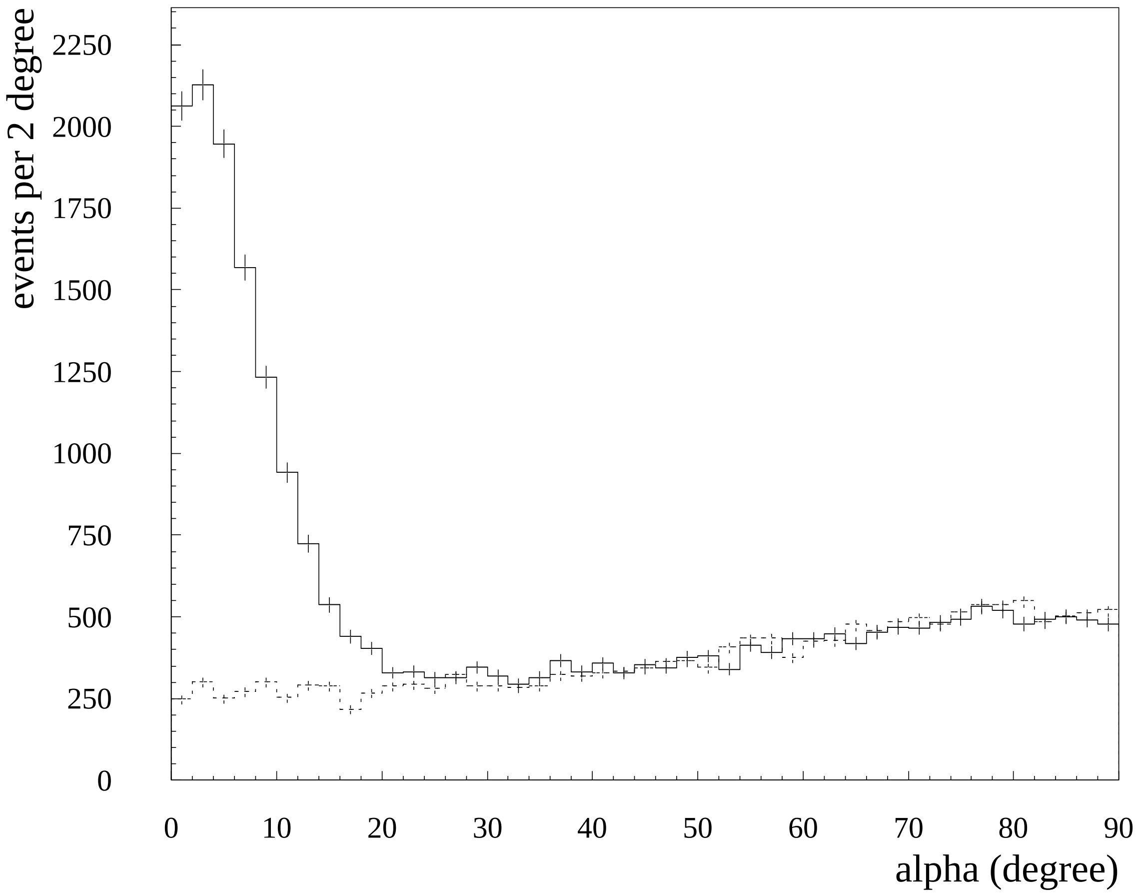

Fig. 1.— The alpha distribution for on-source events (above $\approx$ 1 TeV) shown by the solid line and background events (off-source, dashed line) for the 30.8 hours of observations of flaring states of Mrk 421. The orientation angle alpha is defined as the angle between the major axis of an elliptical γ-ray image and the source position.

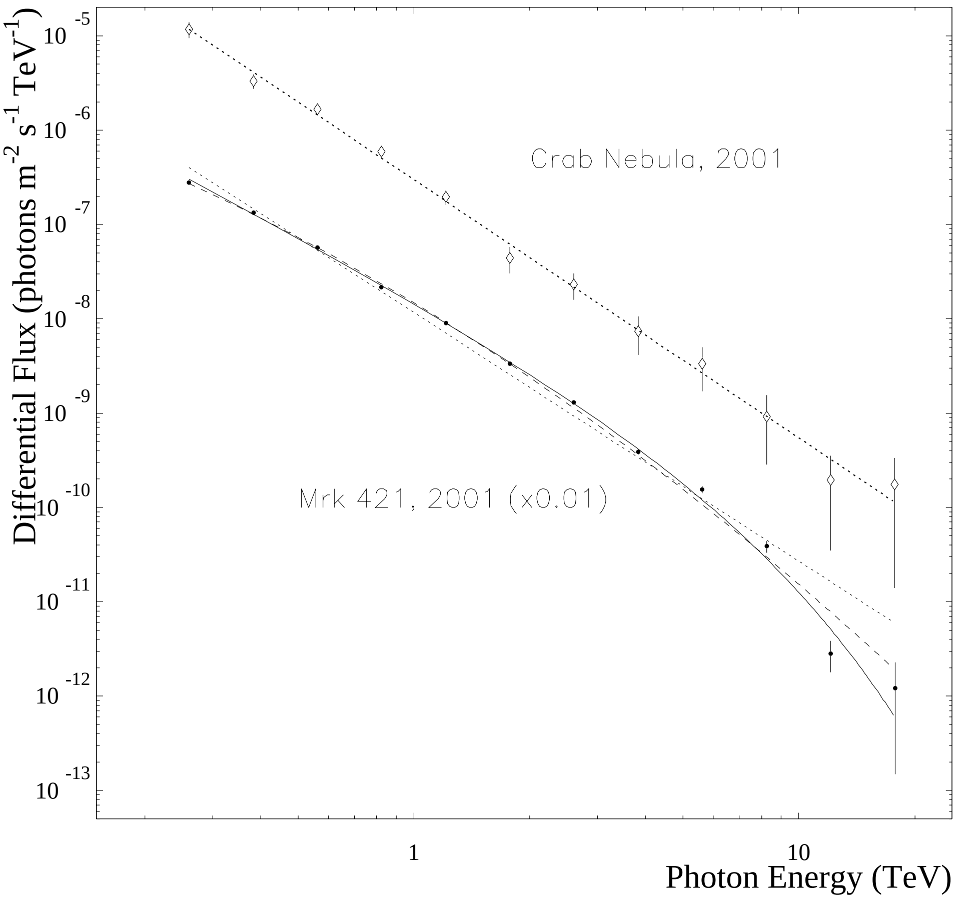

Fig. 2.— The energy spectra of Mrk 421 (filled circles) and the Crab Nebula (diamonds) for the 2001 data set are shown. The dotted lines correspond to power law fits, the dashed line (Mrk 421) corresponds to a parabolic fit, and the solid line is the result from a fit with an exponential cutoff. Note that the Mrk 421 spectrum has been offset by a factor of 0.01 in flux for clearer presentation, and errors shown include only statistical uncertainty.

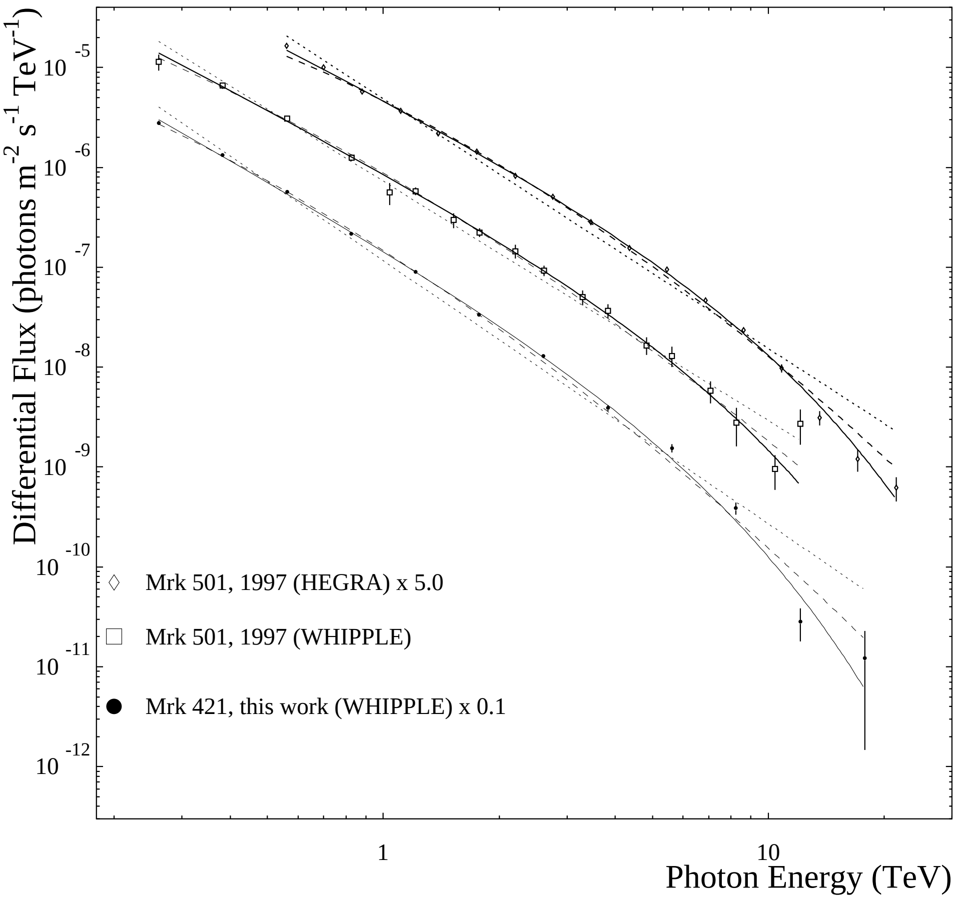

Fig. 3.— A comparison of the Mrk 501 spectra published by the Whipple (Samuelson et al. 1998) and the HEGRA collaboration (Aharonian et al. 1999a) and the Mrk 421 spectrum (this work) is shown. The dotted lines indicate power law fits, the dashed lines are parabolic fits and the solid lines show the power law plus exponential cutoff fits. A common feature to all three spectra is a cutoff at 4 - 6 TeV. Also note that both the Mrk 501 spectrum (Aharonian et al. 1999a) and the Mrk 421 spectrum reported in this paper are not well described by a parabolic spectrum. Also note that spectra have been offset for clearer presentation.